TEST OPERATIONS PROCEDURE

Change 1   3 April 2012
TOP 01-1-014A
DTIC AD No:

RIDE DYNAMICS AND EVALUATION OF HUMAN EXPOSURE TO
WHOLE-BODY VIBRATION

TOP 01-1-014A, 29 November 2011, is changed as follows:

1.   The following elements of TOP 01-1-014A, 29 November 2011, are changed (added at end
of paragraph 4.2.d):

The total VDV (VDV_{total}) from separate events can be calculated with the 4-th root of the sum of
the VDV_i of the individual events taken to the fourth power, or expressed as:

$$VDV_{total} = \left\{ \sum_i VDV_i^4 \right\}^{1/4}$$

The total VDV from a repeating a specific condition can be estimated by using an individual
VDV_i value multiple times in the above expression. For example, the total VDV value from N
impacts on a half round at a specific speed can be estimated with the following expression:

$$VDV_{total} = \left\{ N \cdot VDV_i^4 \right\}^{1/4}$$

where:
          VDV_i is the VDV from a single impact at a particular speed.

          VDV_{total} is the total VDV which is being calculated

          N is the number of impacts for which the total VDV is being calculated

2.   The proponent of this change is the Range Infrastructure Division (CSTE-TM), US Army
Test and Evaluation Command, 2202 Aberdeen Boulevard, Aberdeen Proving Ground, Maryland
21005-5001.

3.   After posting the new change, file subject change notice in front of every electronic or
printed paper copy of subject TOP in your possession, for reference purposes.

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Marginal notations are not used in this revision to identify changes with respect to the previous issue due to the extent of the changes.

14. ABSTRACT
This TOP describes methods for evaluating the ride dynamics or ride quality and whole body vibration (WBV) of ground vehicles. Ride dynamics and WBV pertain to the sensation or feel of the passengers in the environment of a moving vehicle. The technique for evaluating the ride dynamics and WBV involves the use of instrumented seats or ride quality pads which contain accelerometers molded in a rubber disk to provide measurements in three mutually perpendicular axes. The instrumented seats are occupied by the normal vehicle crew. Ride dynamics data are acquired while the vehicle traverses various test courses at pre-determined speeds. The data are then processed by performing Fourier transformations and creating Power Spectral Density (PSD) files for the individual test runs.

15. SUBJECT TERMS

Absorbed Power	ISO 2631-1: 1997	ISO 2631-5
Power Spectral Density	Ride Dynamics	

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U.S. ARMY TEST AND EVALUATION COMMAND
TEST OPERATIONS PROCEDURE

RIDE DYNAMICS AND EVALUATION OF HUMAN EXPOSURE TO
WHOLE-BODY VIBRATION

1.   SCOPE.

This Test Operations Procedure (TOP) describes methods for evaluating the ride dynamics or ride quality of ground vehicles as well as the vehicle occupants' exposure to Whole-Body Vibration (WBV). Ride dynamics pertains to the sensation or feel of the passengers in the environment of a moving vehicle. Ride quality is a measure of vehicle mobility (linking vehicle speed and terrain roughness) while WBV exposure is concerned with the adverse health effects or serious injuries that may occur as a result of vibration exposure. The technique for collecting data to be used for either ride dynamics or WBV exposure assessments is similar. The vehicle seats are instrumented with ride quality pads which contain accelerometers molded in a rubber disk to provide measurements in three mutually perpendicular axes. The instrumented seats are occupied by a vehicle crew. Data are acquired while the vehicle traverses various test courses at pre-determined speeds. The collected raw data are processed according to three analysis techniques. For the ride dynamics analysis, the data are processed by performing Fourier transformations and creating frequency weighted Power Spectral Density (PSD) files for the individual test runs. The ride dynamics analysis techniques are described in Paragraph 4. For WBV exposure analysis, the data are processed via specifications called out in International Standards Organization (ISO) 2631-1[1]* and ISO 2631-5[2]. The analysis technique for ISO 2631-1 is described in Paragraph 4.2 and the analysis technique for ISO 2631-5 is described in Paragraph 4.3.

2.   INSTRUMENTATION.

2.1   Ride Quality Pads.

Vibration will be sensed by accelerometers mounted in ride quality pads, which will be placed in designated vehicle seats. The ride quality pads are typically fabricated in-house and contain three uniaxial piezoresistive accelerometers (vertical, transverse, and longitudinal) mounted in a rubber disk. The primary requirements of these pads are that they should not adversely affect occupant comfort and shall not significantly distort the buttock-cushion load distribution. These pads generally conform to the suggested design of Society of Automotive Engineers (SAE) J1013[3], as shown in Figure 1. The semi-rigid disk is fabricated of molded rubber of approximately 80 to 90 durometer (A Scale).

2.2   Other Measurement Locations.

Additional vibration (acceleration) measurements should be made to provide a "dynamic map" from the terrain surface to the seat (frame and floor of the vehicle are also used) for correlation with future testing that may not have seat pad instrumentation (e.g., endurance test vehicles). As a minimum, acceleration measurements should be made in the vertical axis at one unsprung mass (suspension) location near the tire, the sprung mass corresponding to the previous location (frame), and the base of any instrumented seat. All additional accelerometers should be DC coupled devices.
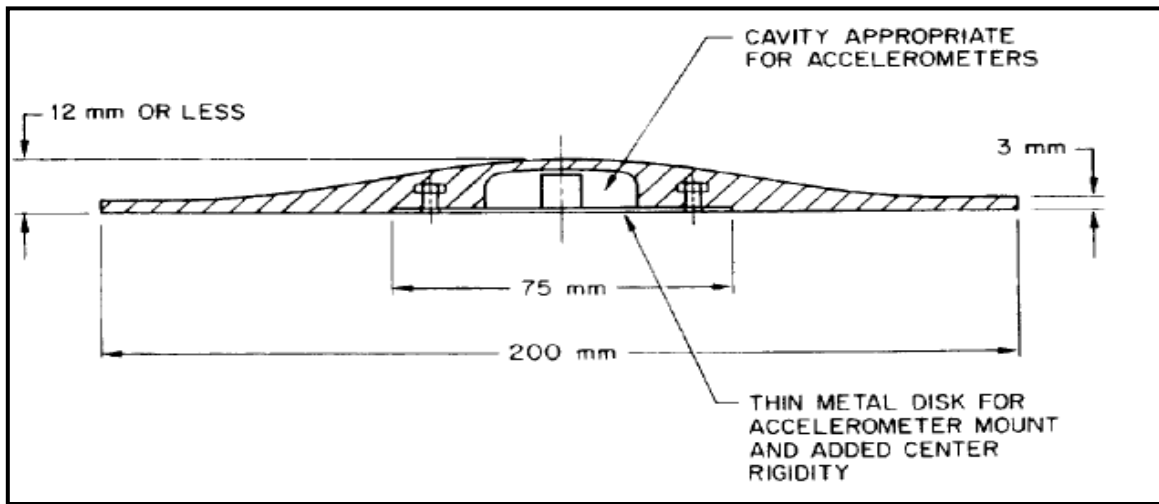
*Superscript numbers correspond to Appendix G, References.

Figure 1. Suggested design for ride quality pad.

2.3   Vibration Measurement Axes.

Vibrations are to be measured utilizing the seat pad mounted accelerometers in the vertical (z axis), fore/aft (x axis), and lateral (y axis) directions. The vibration measured along these three mutually perpendicular axes pass through a point on the interface between the seated crew member and the seat. This orientation is shown in Figure 2.
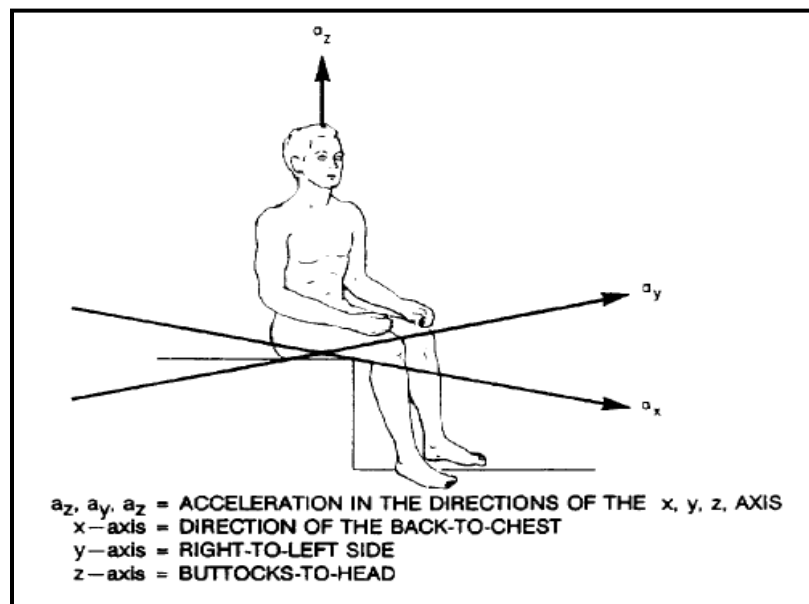

Figure 2. Measurement axes.

2.4   Test Subject Anthropometry and Seat Adjustment.

Measurements will be made at the driver's seat and at other crew positions as required by the vehicle specification and/or the detailed test plan. The sex, height, and weight of each occupant of the instrumented seats, as well as the seat location within the vehicle, will be recorded. Test subjects should preferably have a height and weight between the Army 5th percentile female and 95th percentile male, and should not be outside the height and weight range allowable within the Department of Defense (DOD) Handbook (HDBK)-743A[4], except for unique circumstances (e.g., limited personnel resources with required skill). The US Army Anthropometry measurements are provided in Table 1. The seat, if adjustable, will be properly adjusted per manufacturer's specification. Subjects will maintain contact between the seat pad and buttocks at all times. Loss of contact during the test will require a retest for that condition. Other (non-instrumented) seats will be filled with an appropriate dummy load to simulate the weight of a crew member.

TABLE 1. US ARMY ANTHROPOMETRY

CATEGORY	HEIGHT		WEIGHT	
	centimeter (cm)	inches (in.)	kilogram (kg)	pound (lb)
Male - Max	203	80	113[a]	250[a]
Female - Min	147	58	41	91
Male – 95%	187	73.5	98	216
Female – 5%	153	60.2	49	109

[a] Age dependent - max age (40+) shown

2.5   Accelerometers and Signal Conditioning.

The pad and ancillary accelerometers together with their associated signal conditioning shall be capable of measuring root-mean-square (rms) accelerations in the 0.1 to 100 Hertz (Hz) bandwidth. An on-board or telemetry data acquisition system will be used to acquire data while the vehicle is operated on the test courses. All data will be digitized at a minimum of 400 samples per second per channel after having been low-pass filtered at a minimum of 100 Hz. Ensure low pass filters are adequate to prevent aliasing of the data. If a half-round obstacle requirement must be met, a vertical accelerometer will be installed at the base of the driver's seat to comply with historical data. Other locations (e.g., on the seat) may be instrumented as required by the vehicle specification and/or the detailed test plan.   This (half-round obstacle) accelerometer will be low-pass filtered (post test) at 30 Hz (Paragraph 4.4). Amplifiers should be adjusted to provide an acceleration resolution of approximately 0.01 g. Analysis parameters should be chosen so that frequency domain resolution is 0.2 Hz or less.

2.6   Acceleration Units.

Acceleration units for analysis will be meters/sec^2 for ISO-2631-1/ISO 2631-5 computations, ft/sec^2 for absorbed power computations and "g" for other acceleration computations.

2.7   Data Validation.

Prior to analysis, data from each transducer and each data run will be checked for stationarity and for errors such as noise, amplifier drift, clipped data, etc. Procedures used for data validation will be presented in the test report.

2.8   Length of Data Run.

The precision of acceleration spectral estimates is related to the length of the data run. Data should generally be recorded for a period of at least one minute unless restricted by test course length and vehicle speed.

2.9   Vehicle.

The test vehicle will be described by recording the information in Appendix A.

2.10   Vehicle Speed.

Vehicle speed will be recorded by an auxiliary, calibrated speed sensing system to an accuracy of $\pm$ 0.2 kilometers per hour (km/hr) (0.1 miles per hour (mph)). The test speed will be held constant (to the extent possible) at the target speed for the duration of the data run. The speed Coefficient of Variation (COV (standard deviation/mean)) for each data run should be equal to or less than 0.10.

2.11   Test Courses for Ride Quality.

Test courses used for ride quality should have a wave number spectrum (power spectral density function of the instantaneous terrain vertical profile in the spatial domain) with a slope of approximately -2 in the log-log domain. The rms roughness value will be computed as the square root of the integral of the wave number spectrum and will be computed between wave numbers that cover the frequency range of interest (typically 0.5 to 80 Hz). The affected wave numbers are a function of vehicle speed (single wheel frequency), and integration band wave numbers between approximately 0.016 and 2.0 (wavelengths of 0.5 feet to 64 feet) will suffice for speeds up to 40 km/hr (25 mph). The lower integration band wave number should be reduced to 0.01 (wavelength of 100 feet) for speeds between 40 and 56 km/hr (25 and 35 mph).

2.12   Test Courses and Speeds for WBV Analysis.

Data must be collected in a manner that is representative of the mission profile of the vehicle and is typical of the expected exposures. Duration of measurements shall be sufficient to ensure

statistical precision. Whole-body vibration data must be collected in accordance with ISO 2631-1 and ISO 2631-5. Refer to ISO 2631-1 and ISO 2631-5 for complete data collection guideline details. In order to properly assess health effects from exposure to WBV, the vehicle should be tested under its normal operating conditions. Vibration data will be recorded on test courses with vehicle speeds and vehicle maneuvering scenarios analogous to the Operational Mode Summary/Mission Profile (OMS/MP). For example, if the vehicle's OMS/MP states the vehicle will operate on primary, secondary, and cross country terrain, then vibration data must be collected on test courses that represent each of the three terrains. If the vehicle's mission profile calls for speeds on primary terrain up to 50 mph, then the vehicle should be tested at increments of 10 mph up to 50 mph on primary terrain. Coordination with the vehicle's program office to determine test courses and speeds that best represent the vehicles normal operating conditions is recommended. If program office guidance is not forthcoming, Table B-1 in Appendix B contains the minimum requirements for speed and course terrains the vehicle needs to traverse to complete the WBV data set.

2.13 <u>WBV Analysis of Operational Mode</u>.

Vehicles that produce WBV in environments other than traversing terrain are to be tested under conditions that replicate the operational environment in which the WBV is produced. For example, backhoes with breaker attachments generate large amounts of vibration while the vehicle is stationary. A proper assessment will include WBV data collected while the backhoe's breaker is in operation. Table B-2 in Appendix B provides general examples of Operational Mode Analysis.

2.14 <u>Test Conduct</u>.

a. Acceleration and speed data will be acquired as the vehicle is driven over each test course at multiple constant speeds as described in the test plan for a period of at least 1 minute (when not limited by test course length) for the ride dynamics courses, and for a sufficient period of time to capture the shock event when negotiating the half-round obstacles. A speed increment of approximately 3 km/hr (2 mph) should be used because vertical absorbed power generally increases as a power law function of speed for a given rms roughness (e.g.,Absorbed Power ~ k*Speed^5). Following each data run, the crew will be polled to ensure that it is safe to proceed to the next speed. Each instrumented crew member's seat vertical acceleration data will be processed at the test site after each data run to provide an absorbed power value. The test on each course will be considered as completed when the driver's vertical absorbed power equals or exceeds 15 watts, when any crew member believes that an increase in speed would create a hazardous condition, or when the course speed limit is reached (applicable only to relatively smooth courses). The limit value of 15 watts was chosen to satisfy the requirements of at least one Army vehicle (a ride specification based on "9 to 12 watts") and to enhance the ride-speed distribution for the health hazard assessment (Paragraph 5). Data runs that produced absorbed power values from above 1 watt to the maximum speed run will be repeated to enhance data confidence.

b. To evaluate the shock input test criteria, the half-round obstacles should be traversed with either wheel or track paths crossing the obstacle simultaneously. To evaluate vehicle roll

dynamics and suspension characteristics, additional data runs can be performed with a single wheel or track path crossing the obstacle while the other wheel or track path remains on level ground.

3.   VIBRATION EVALUATION.

a.   Vibration evaluation will be performed using two techniques; an ISO technique which deals with health effects of exposure to vibration, and an absorbed power technique which is used to describe speed limiting effects over rough terrain.

b.   The principal factors that combine to determine the degree to which human exposure to whole body vibration will be acceptable is described in ISO 2631-1. Four possible effects of vibration include Degraded Health, Comfort, Perception and Motion Sickness. The frequency ranges of these effects are:

(1) 0.5 Hz to 80 Hz for Degraded Health, Comfort and Perception.

(2) 0.1 Hz to 0.5 Hz for Motion Sickness.

c.   Unless required by the test plan, only the issue of degraded health will be evaluated. This type of vibration is transmitted to the human body as a whole through the supporting surfaces of the buttocks, back, and feet of a seated person in a moving wheeled or tracked vehicle. Vibration is measured according to the coordinate system originating at a point from which vibration enters the human body. The coordinate system for the alignment of the vibration transducers is shown in Figure 2. The three principal areas of contact for seated persons are: (1) the supporting seat surface, (2) the seat back, and (3) the feet, but only the seat data are of interest for degraded health analysis. Seat data are also the basis for the absorbed power analysis. Vibration transmitted to the body through a non-rigid material, like a seat cushion, is measured with the transducer interposed between the person and the principal contact areas of the surface. This is achieved by mounting the transducers within a ride quality pad as described in Figure 1.

4.   ANALYSIS TECHNIQUES.

4.1   Absorbed Power Technique.

a.   Another technique for evaluating human response to vibration or ride quality is the computation of absorbed power. It is a measure of the rate at which energy is absorbed by a human subjected to ride vibration. It is accepted as a measure of human tolerance to vibration for military vehicles negotiating rough terrain. The absorbed power for a given location and axis is computed by multiplying the acceleration power spectral density spectrum by the appropriate transfer function and integrating the resultant spectrum. An advantage of this approach is that average absorbed power is a scalar quantity and can be summed in complex multi-degree of freedom systems to yield a single value describing the total average absorbed power. Typically a standard ride quality test procedure involves determining the speed at which the vertical average absorbed power reaches an upper limit of 6 watts for different types of terrain at selected crew

location seats. The terrain is usually characterized by the surface roughness reported as inches or centimeters rms. The vehicle speed as a function of terrain roughness obtained from this process is used as one of the mobility limiting factors in the North Atlantic Treaty Organization (NATO) Reference M obility M odel. M ilitary v ehicle specifications frequently in clude r ide q uality requirements based on a bsorbed power (e.g., the vehicle must be capable of producing a ride of 6 watts or less at the driver's seat in the vertical axis for a given speed and surface roughness).

    b.   The absorbed power in each axis will be calculated from:

$$P = \sum_{1}^{n} (C_i) \, A_i^2$$

where:

        P = Absorbed power, watts.

        A_i = rms acceleration in ft/sec^2 within the ith spectral band.

        $C_i = K_1 K_0 (F_1 F_4 - F_2 F_3) / (F_3^2 + W_i^2 F_4^2)$.

        W_i = Frequency, radians/second.

        F and K values = Calculated from Appendix C.

    c.   The result is a frequency weighting, scaling and integration of the acceleration power spectral density. The weighting functions are shown (by axis) in Figure 3. The factors have been normalized to a value of 1.0 to show frequency without the appropriate scaling.

    d.   For each test course, the absorbed power will be plotted as a function of speed. Specification requirements are generally written in terms of the driver's vertical absorbed power (only), but the following technique will be applied to other locations and axes, if applicable. A non-linear interpolation or a power law ($y = ax^b$, linear fit in a log-log domain,) or nth degree polynomial curve fit will be performed and the speed at which an absorbed power of 6 watts is achieved, will be interpolated from the data set. Absorbed power values of less than 1 watt or greater than 10 watts will not be used in the curve fit process, if possible. The 6-watt speed will then be plotted as a function of terrain roughness rms (a specific value for each test course) to determine a ride quality curve for the vehicle.
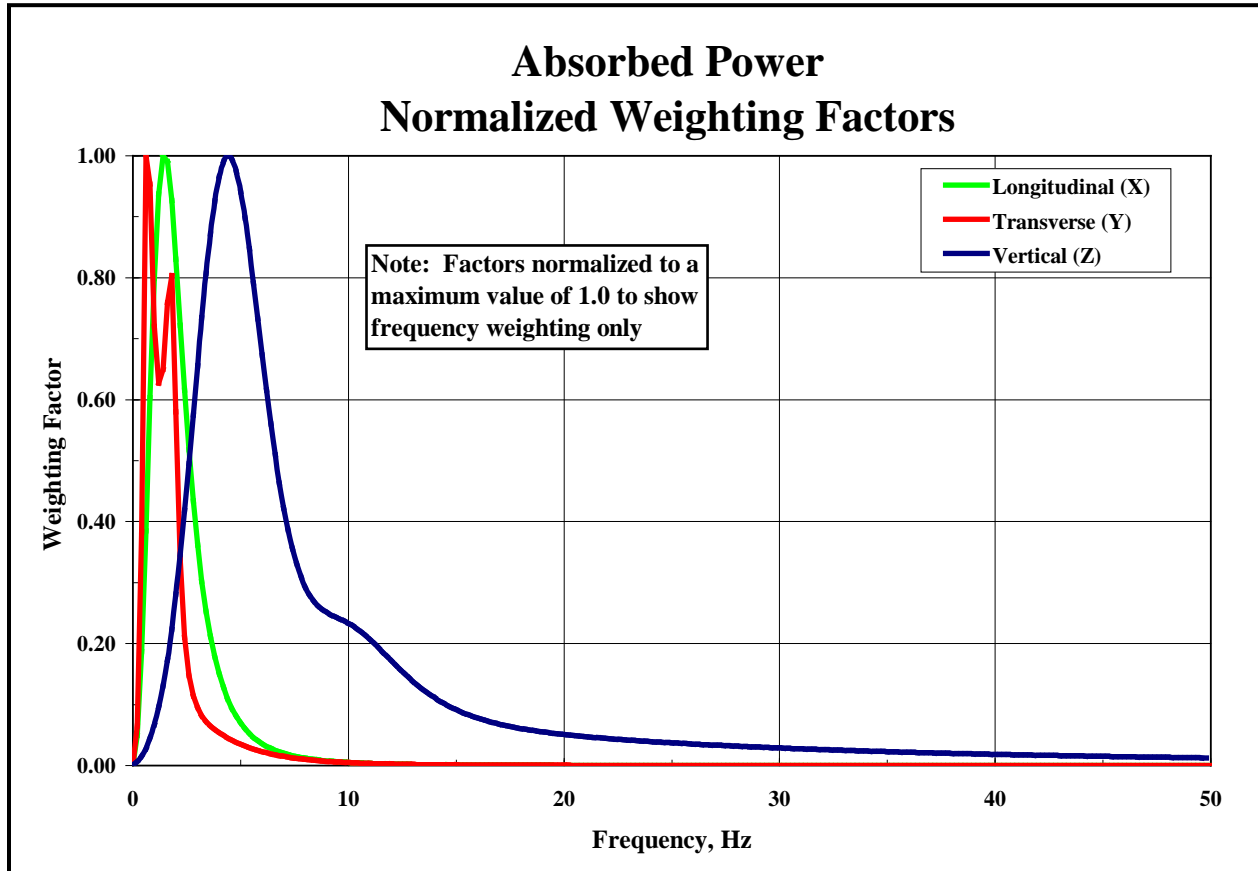
Absorbed Power
Normalized Weighting Factors

Figure 3. Absorbed power normalized frequency weighting factors.

4.2 <u>ISO 2631-1 Technique</u>.

a. The basic evaluation method described in ISO 2631-1 utilizes the weighted rms acceleration. The weighted rms acceleration is expressed in meters per second squared (m/s^2) for translational vibration and radians per second squared (rad/s^2) for rotational vibration. The weighted rms acceleration is calculated in accordance with the following equation or its equivalent in the frequency domain:

$$a_w = \left[\frac{1}{T} \int_0^T a_w^2(t)dt \right]^{\frac{1}{2}}$$

where:

a$_w$(t) is the weighted acceleration (translational or rotational) as a function of time (time history), in m/s^2 or rad/s^2, respectively.

T is the duration of the measurement, in seconds.

    b.   The crest factor may be used to investigate whether or not the basic evaluation method is suitable for describing the severity of the vibration in relation to its effects on human beings. The peak value is determined over the duration of the measurement, i.e. the time period T used for integration of the rms value. The crest factor does not necessarily indicate the severity of vibration. For vibration with crest factors below or equal to 9, the basic evaluation method outlined above is normally sufficient. In cases where the basic evaluation method may underestimate the effects of vibration (high crest factors, occasional shocks, and transient vibration) an alternative technique should be utilized such as the running rms method or the fourth power vibration dose method.

    c.   The running rms method evaluation method takes into account occasional shocks and transient vibration by use of a short integration time constant, for example 1 second. The vibration magnitude is defined as a Maximum Transient Vibration Value (MTVV), given as the maximum in time of $a_w(t_0)$, defined by:

$$a_w(t_0) = \left\{ \frac{1}{\tau} \int_{t_0-\tau}^{t_0} [a_w(t)]^2 \, dt \right\}^{\frac{1}{2}}$$

where:

        $a_w(t)$ is the instantaneous frequency-weighted acceleration.

        τ is the integration time for running averaging.

        t is the time (integration variable).

        t_0 is the time observation (instantaneous time).

    d.   The fourth power vibration dose method is more sensitive than the basic evaluation method by using the fourth power instead of the second power of the acceleration time history as the basis for averaging. The fourth power Vibration Dose Value (VDV) in meters per second to the power 1.75 ($m/s^{1.75}$), or in radians per second to the power 1.75 ($rad/s^{1.75}$), is defined as:

$$VDV = \left\{ \int_{0}^{T} [a_w(t)]^4 \, dt \right\}^{\frac{1}{4}}$$

where:

        $a_w(t)$ is the instantaneous frequency-weighted acceleration.

        T is the duration of measurement.

The total VDV (VDV$_{total}$) from separate events can be calculated with the 4-th root of the sum of the VDV$_i$ of the individual events taken to the fourth power, or expressed as:

$$VDV_{total} = \left\{ \sum_i VDV_i^4 \right\}^{\frac{1}{4}}$$

The total VDV from a repeating a specific condition can be estimated by using an individual VDV$_i$ value multiple times in the above expression. For example, the total VDV value from N impacts on a half round at a specific speed can be estimated with the following expression:

$$VDV_{total} = \left\{ N \cdot VDV_i^4 \right\}^{\frac{1}{4}}$$

where:

VDV_i is the VDV from a single impact at a particular speed.

VDV_{total} is the total VDV which is being calculated

N is the number of impacts for which the total VDV is being calculated

e.   The frequency weighting curves used for various directions of measurement in the calculation of frequency-weighted acceleration for the seat surface as outlined in ISO 2631-1 are provided in Appendix D and Figure 4.
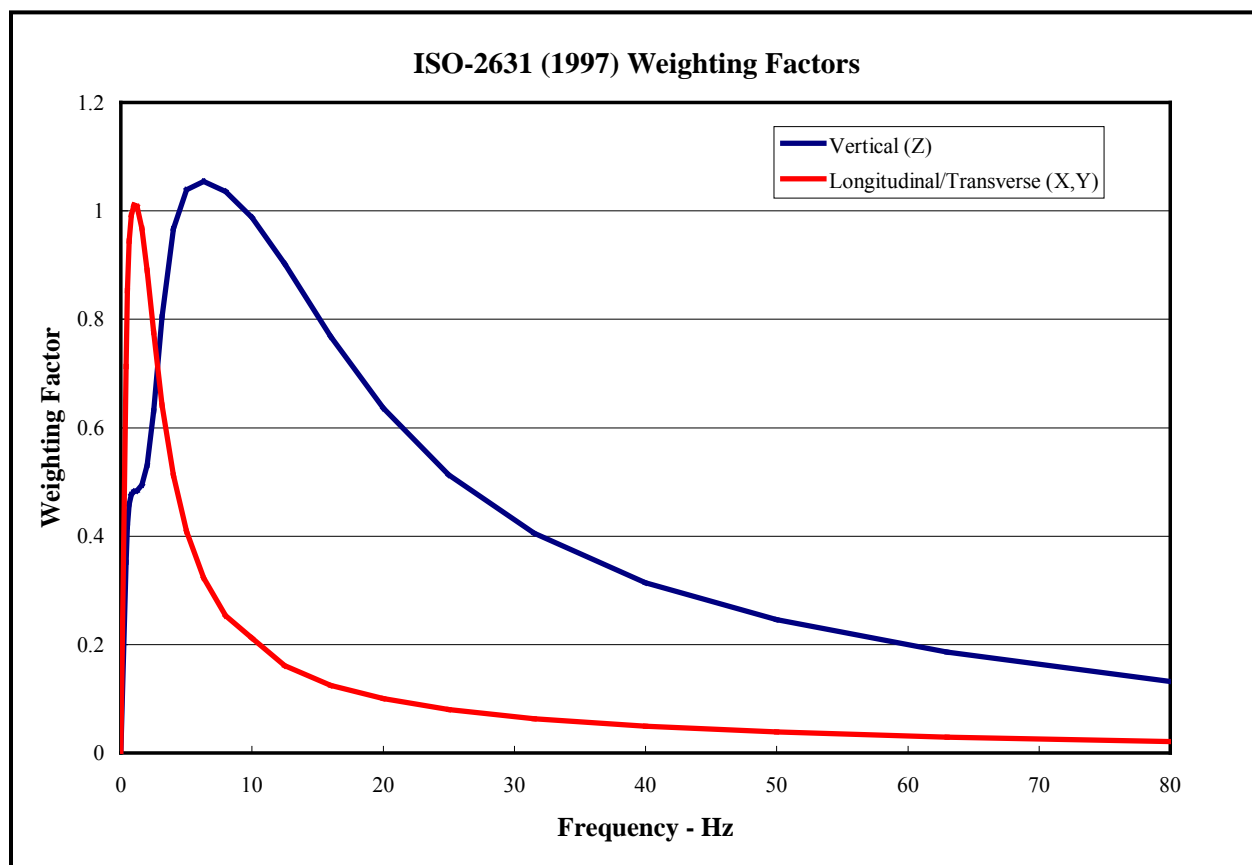
Figure 4. ISO 2631-1 frequency weighting factors.

    f.   Daily vibration exposure limits are determined from the weighted acceleration, a_w, in each axis. The assessment is made independently for each axis, but the vector sum is used if the weighted accelerations from two or more axes are comparable. The evaluation is made using the frequency weighting factors shown in Appendix D with the multiplying factors as shown in Table 2.

TABLE 2. MULTIPLYING FACTORS

AXIS	FACTOR
X,Y	1.4
Z	1.0

    g.   Exposure times for three conditions – no documented health risks, caution zone for health risks, and health risks likely are calculated from the weighted acceleration as follows:

(1) No documented health risks: Exposure time = $1.5/a_w^2$.

(2) Health risks likely: Exposure time = $6.0/a_w^2$.

(3) Caution zone for health risks: Exposure time > $1.5/a_w^2$ and < $6.0/a_w^2$.

(4) For example: let a_w = 2.0 m/s^2.

(a) Exposure time = 0.4 hours for no documented health risks.

(b) Exposure time = 0.4 to 1.5 hours for a health risk caution.

(c) Exposure time = 1.5 hours for a likely health risk.

(d) Thus, an exposure (per 24 hours) to this level of vibration for less than 0.4 hours should produce no health risks, an exposure between 0.4 hours and 1.5 hours will result in a health risk caution, while an exposure of 1.5 hours or greater will create a likely health risk.
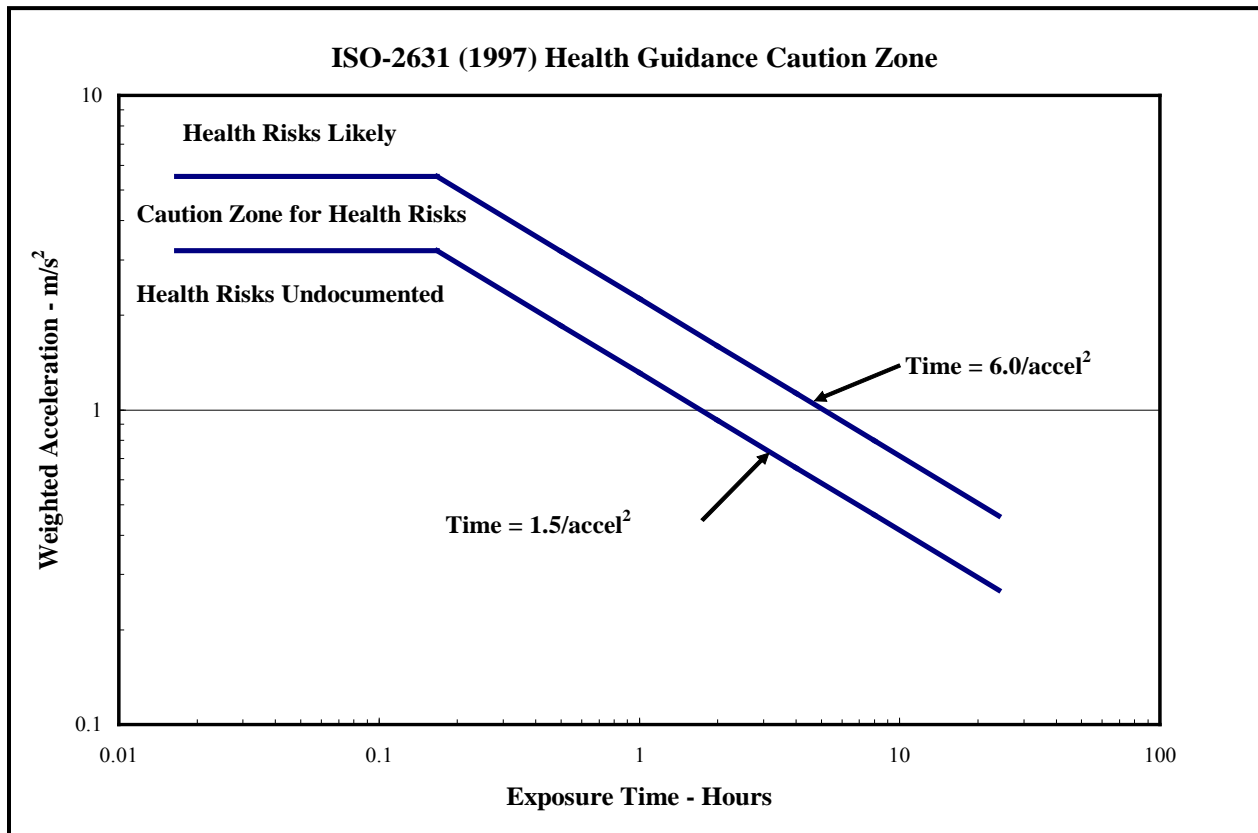
h. The health guidance caution zone is shown in Figure 5.

Figure 5. Health guidance caution zone.

4.3   ISO 2631-5 Multiple Shock Method.

    a.   The method conveyed in ISO 2631-5 is an attempt to quantify whole-body vibration containing multiple shocks in relation to human health. The assessment method described in ISO 2631-5 presumes an individual is in good physical condition and is maintaining and upright and unsupported seated posture. Specifically this method is meant to focus on the lumbar spine. Different postures will result in different responses in the spine. The method attempts to create predictions about the number of years for which an individual can be subjected to a sample time history prior to the onset of adverse health effects. However, in the introductions the authors identify that this assessment method and related models have not been epidemiologically validated.

    b.   The calculation of the spinal response acceleration dose involves the following steps: calculation of the human response of the spine, counting the number and magnitudes peaks, calculation of an acceleration dose by application of a dose model related to the Palmgren-Miner fatigue theory. The spinal response to the seat bottom triaxial input is estimated with predictive models. The spinal response in the horizontal plane is approximated by a linear single degree of freedom lumped parameter model. The spinal response in the vertical axis is approximated with a non-linear recurrent neural network model. The model coefficients used for the vertical model are specific to a sampling rate of 160 samples per second. The data collected for this test were re-sampled to 160 samples per second.

    c.   The acceleration dose, D_k, in meters per second squared in the k-direction is defined as:

$$D_k = \left[\sum_i A_{ik}^6 \right]^{1/6}$$

where:
    A_{ik} is the ith peak of the response acceleration $a_{lk}(t)$.

    d.   The average daily dose, D_{kd}, in meters per second squared, can be computed with the following:

$$D_{kd} = \left[\sum_{j=1}^{n} D_{kj}^6 \frac{t_{dj}}{t_{mj}} \right]^{1/6}$$

where:
    D_{kj} is the acceleration dose for the jth unique period within a day.

    t_{dj} is the duration of the daily exposure to condition j.

    t_{mj} is the period over which D_{kj} was measured.

e.   As s tated, t he ISO 263 1-5 m ethod a pplies t he P almgren-Miner a pproach f or t he evaluation o f t he ef fects of i nternal p ressure c hanges on t he s pine.   The m ethod relies upon experimental data which has shown the Palmgren-Miner exponent varies for different tissues (5 to 14 f or bone s, 20 f or c artilage).   F or t he pu rpose of e stimating a dverse h ealth effects a conservative e xponent of 6 w as us ed.   From t his a ssumption t he c onstants a nd s implifying equations are developed to predict the life cycle response of human tissue. The daily equivalent static compression dose, S_{ed}, in megapascals is obtained with the D_{kd} value calculated earlier:

$$S_{ed} = \left[\sum_{k=x,y,z} (m_k D_{kd})^6 \right]^{1/6}$$

where:

$m_x = 0.015$ MPa/(m/s^2).

$m_y = 0.035$ MPa/(m/s^2).

$m_z = 0.032$ MPa/(m/s^2).

f.   A factor R is defined to account for the repeated exposure to the same environment for a num ber of years. T he m ethod attempts to ta ke in to a ccount th e d ifferences in in itial tis sue strength related to the age of the seat occupant. As the exposure time increases the muscle tissue reduces in strength. For this reason R must be calculated sequentially:

$$R = \left[\sum_{i=1}^{n} \left(\frac{S_{ed} N^{1/6}}{S_{ui} - c} \right)^6 \right]^{1/6}$$

where:

N is the number of exposure days per year.

i is the incremented year count from the beginning of exposure.

n is the number of years of exposure.

c is a constant representing the static stress due to gravitational force.

b is the age at which the exposure starts.

S_{ui} is the ultimate strength of the lumbar spine for a person of age (b+i) years.

g.   The value S_{ui} is indented to account for the variation in vertebrae bone density, which normally reduces with age. In-vitro studies were used to derive the relationship between S_{ui} (in megapascals) and b+i (years):

$$S_{ui} = 6.75 - 0.066(b+i)$$

h.   The method provides some guidance on the interpretation of the S_{ed} and R values. For instance, if the seat occupant is subjected to 240 days of exposure per year for a lifetime, a S_{ed} value of 0.5 MPa indicates a low probability of an adverse health effect. A S_{ed} value of 0.8 MPa indicates a high probability of an adverse health effect.   These would correspond to R values of 0.8 and 1.2 respectively. Obviously the severity of S_{ed} will depend on the presumed duration of the daily exposure, t_{dj}, which the shorter sampling time, t_{mj}, is intended to represent. Often the daily exposure time is unknown and will depend on the severity of the duty to which the occupant is exposed. Obviously future work would benefit from a better understanding of real world exposures. Similarly assumptions must be made about the starting age and number of years of exposure to which an occupant is subjected. For an enlisted soldier, an average starting age of 21 years with 21 years of service can be a good presumption.

4.4   Half-Round Obstacle Technique.

The peak acceleration from the vertical accelerometer at the base of the driver's seat will be low-pass filtered at 30 Hz (4-pole Butterworth filter forward and backward to preserve phase) and the resulting peak acceleration will be plotted as a function of speed for each half-round obstacle. The speed at which a peak value of 2.5 g's is reached will be determined by a on-linear interpolation or curve fitting technique as described above.

5.   HEALTH HAZARD ASSESSMENT AND DATA FILE STRUCTURE.

a.   The collected vibration data should be stored in simple text files. The data collected must be in British Columbia Research (BCR) format, which is a text file with the extension ".BCR."   The filenames must have the ".BCR" extension because it is the only extension recognized by the Jolt software.   The files should contain two sections, Header and Data, and should be formatted as shown in Appendix E.

b.   The health hazard assessment is based on the vehicle's mission profile, which is reflected in the test course mileage breakdown of the endurance test. The same ride data previously described will be collected on the endurance test courses following the guidelines of Paragraph 2.11. To improve test efficiency, data from remote test courses need not be acquired if the ride is judged to be similar to that of convenient test courses (e.g., data from Aberdeen Test Center Munson Gravel course can be used as a replacement for the Churchville "C" course).

c.   An exposure time for each test speed (by test course) will be determined from a measured probability distribution function of a recent endurance test of a similar vehicle or will be computed using the assumption of a beta distribution. The beta distribution is defined as:

Probability Density Function

$$f(X) = \frac{X^{\alpha-1}(1-X)^{\beta-1}}{B[\alpha,\beta]}$$

where $B[\alpha,\beta]$ is the beta function

with parameters α and β, given by

$$B[\alpha,\beta] = \int_0^1 X^{\alpha-1}(1-X)^{\beta-1} dX$$

    d.   The parameter alpha is based on the ratio of the average speed to the maximum speed and is selected from Table 3. The parameter beta is calculated using an optimization routine such that the resultant average speed equals the desired average speed. An example using a minimum speed of 10 km/hr (6 mph), an average speed of 23 km/hr (14 mph), and a maximum speed of 32 km/hr (20 mph) is shown in Figure 6.

TABLE 3. VALUES OF ALPHA

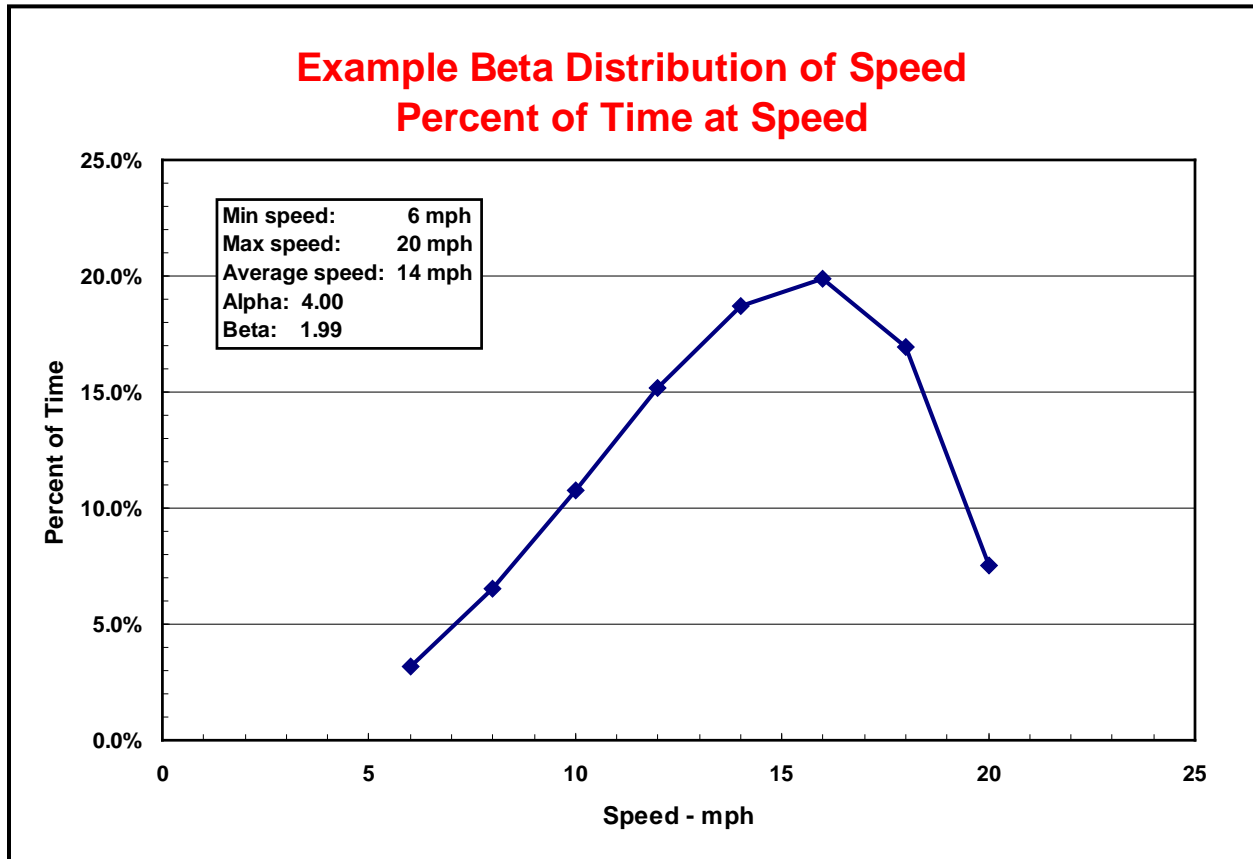| RATIO OF AVERAGE TO MAXIMUM SPEED	ALPHA
10%	0.2
20%	0.5
30%	0.75
40%	1.25
50%	2
60%	3
70%	4
80%	6
90%	13

Figure 6. Example beta distribution.

e.   The exposure times for each test speed are combined with the corresponding ride level to compute an overall weighted acceleration using (equation B3 from ISO 2631-1):

$$a_{ws} = \left[\frac{\sum a_{wi}^{2} * T_i}{\sum T_i} \right]^{\frac{1}{2}}$$

where:

a_{ws} = equivalent vibration magnitude (rms acceleration in m/s^2).
a_{wi} = vibration magnitude (rms acceleration in m/s^2) for exposure duration T_i.
T_i = exposure duration, minutes.

f.   The overall weighted acceleration can be used to provide a health hazard assessment by terrain type (primary, secondary, off-road).

APPENDIX A. VEHICLE INFORMATION.

Vehicle Model: _____

Year of Manufacture/Delivery: _____

Serial Number: _____

Odometer Reading: _____

Engine Hours: _____

Type Test Load: _____

Vehicle Weight as Tested:
        Total: _____
        Front Axle: _____
        Intermediate Axle: _____
        Rear Axle: _____

Tire Information:
        Front:
                Manufacturer: _____
                Size: _____
                Type: _____
                Pressure: _____
        Rear:
                Manufacturer: _____
                Size: _____
                Type: _____
                Pressure: _____

Seat Description:
        Driver: _____
        Passenger: _____

Seat Setting:
        Driver: _____
        Passenger: _____

Condition of the Vehicle:
        General Comments:
_____
_____

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APPENDIX B. WBV TEST COURSES AND OPERATIONAL MODE EXAMPLES.

TABLE B-1. TEST COURSES AND SPEEDS FOR WBV ANALYSIS.

TERRAIN TYPE	COURSE	APPROXIMATE ROUGHNESS (in rms)	TOP SPEED (mph)	SPEED INCREMENT[a] (mph)
Primary	Perryman Paved	0.07	50	10
Secondary	Perryman 1	0.3	35	5
Secondary	Perryman A	0.3	35	5
Cross Country	Perryman 2	0.8	25	5
Cross Country	Perryman 3	2.75	20	5

[a] Test Engineer's discretion.

TABLE B-2. EXAMPLES OF WBV ANALYSIS FOR OPERATIONAL MODE.

VEHICLE TYPE	VEHICLE CAPABILITIES	DATA NEEDS	REASONING
High Mobility Engineer Excavator	Earthmoving machine. Performs backhoe, loader, and bull dozing operations.	Collect data while vehicle is performing bull dozing and backhoe operations.	Multiple shock forces from buckets engaging in operations can transfer to seat.
XM1157 10-ton Dump Truck	Transport and spread up to 20,000 pounds of aggregate.	Collect test course and speed data while vehicle is loaded and unloaded.	Weight of aggregate will affect WBV exposure due to added weight on suspension system of vehicle.
Airborne Scraper and Water Distribution System (ASWDS)	ASWDS performs earthmoving road construction and water distribution functions.	Collect movement data while simulating scraping operations, unloaded and loaded water operations.	Scraping operations will impart significantly more WBV into vehicle cab than the water distribution.
Bituminous Material Paving Machine (BMPM)	Performs paving operations.	Simulating paving operations by loading hopper and activating extended screed.	Added load and extended screed may shift center of gravity, resulting in different WBV exposure.

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APPENDIX C. ABSORBED POWER CONSTANTS.

Longitudinal (X)

K_0 4.3532

K_1 1.356

W_i $2\pi f_i$

F_1 1.0

F_2 0.219106

F_3 $-0.0185309W_i^2 + 1$

F_4 $-0.00061893W_i^2 + 0.219106$

Note: f_i = Center frequency (Hz) of ith spectral band.

Transverse (Y)

K_0 4.353

K_1 1.356

W_i $2\pi f_i$

F_1 $0.24052124 \times 10^{-3}W_i^4 - 0.066974483W_i^2 + 1$

F_2 $0.57384538 \times 10^{-5}W_i^4 - 0.50170413 \times 10^{-2}W_i^2 + 0.33092592$

F_3 $-0.14979958 \times 10^{-5}Wi^6 + 0.0010088882W_i^4 - 0.10108617W_i^2 + 1$

F_4 $-0.1713749 \times 10^{-7}W_i^6 + 0.53137351 \times 10^{-4}W_i^4 - 0.011096507W_i^2 + 0.33092592$

Note: f_i = Center frequency (Hz) of ith spectral band.

APPENDIX C. ABSORBED POWER CONSTANTS.

Vertical (Z)

K_0 4.3537

K_1 1.356

W_i $2\pi f_i$

F_1 $-0.10245\text{x}10^{-9}W_i^6 + 0.17583\text{x}10^{-5}W_i^4 - 0.44601\text{x}10^{-2}W_i^2 + 1$

F_2 $0.12882\text{x}10^{-7}W_i^4 - 0.93394\text{x}10^{-4}W_i^2 + 0.10543$

F_3 $-0.45416\text{x}10^{-9}Wi^6 + 0.37667\text{x}10^{-5}W_i^4 - 0.56104\text{x}10^{-2}W_i^2 + 1$

F_4 $-0.21179\text{x}10^{-11}W_i^6 + 0.51728\text{x}10^{-7}W_i^4 - 0.17947\text{x}10^{-3}W_i^2 + 0.10543$

Note: f_i = Center frequency (Hz) of ith spectral band

APPENDIX D. ISO 2631-1 WEIGHTING FACTORS.

TABLE D-1. WEIGHTING FACTORS.

ONE-THIRD OCTAVE CENTER FREQUENCY (Hz)	WEIGHTING FACTORS	
	LONGITUDINAL/TRANSVERSE (X,Y)	VERTICAL (Z)
0.2	0.243	0.121
0.25	0.365	0.182
0.315	0.530	0.263
0.4	0.713	0.352
0.5	0.853	0.418
0.63	0.944	0.459
0.8	0.992	0.477
1.0	1.011	0.482
1.25	1.008	0.484
1.6	0.968	0.494
2.0	0.890	0.531
2.5	0.776	0.631
3.15	0.642	0.804
4.0	0.512	0.967
5.0	0.409	1.039
6.3	0.323	1.054
8.0	0.253	1.036
10.0	0.212	0.988
12.5	0.161	0.902
16.0	0.125	0.768
20.0	0.100	0.636
25.0	0.080	0.513
31.5	0.0632	0.405
40.0	0.0494	0.314
50.0	0.0388	0.246
63.0	0.0295	0.186
80.0	0.0211	0.132
100.0	0.0141	0.0887

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APPENDIX E. HEALTH HAZARD ASSESSMENT DATA FILE FORMAT.

E-1. <u>Header</u>.

Each BCR file starts with a header that includes three descriptive groups of information about the test parameters (channel labels, engineering units, sampling rate, etc.). The filename (maximum of 12 characters) appears on the first line of the header. A descriptive title can be placed on the first and second line starting at column 17. Header information is placed in blocks that start with a label that is surrounded by angle brackets: <TEST>, <SAMPLING>, and <CHANNELS>. Blank lines in the header section are ignored.

E-2. <u>Data</u>.

The data section begins with the label <DATA>, followed by a line containing the format of the data (in Fortran style) and then the numeric data itself organized in columns with each column representing one channel of data. The data may be delimited by commas, tabs, or spaces, with one row representing one time sample of all signals. Each data point can have a maximum of seven characters. The best way to accomplish this is to limit the resolution of the data to thousandths (0.001).

E-2.1 The Jolt program is designed to treat each triaxial accelerometer as a single data file. Therefore, for each measurement location, there needs to be a separate BCR data file containing the acceleration data for that location. The Jolt program is also designed to read input from each of the three axes (X, Y, Z) of the accelerometer simultaneously. Therefore, the BCR data file has to contain three columns of acceleration data with the order of X being the first column, Y being the second, and Z being the final column. Data may only span 512 characters across each row of data.

E-2.2. The program requires the acceleration data be in the units of m/s^2. For convenience of the user, and for those files in units other than m/s^2 (such as g's), the user may specify a conversion factor and have the program convert the data to m/s^2. Figure E-1 is an example illustration of the BCR file data structure. Note: You must include keywords as they are shown in red (including colons).

APPENDIX E. HEALTH HAZARD ASSESSMENT DATA FILE FORMAT.

```
A_Sample.BCR      THIS IS A SAMPLE TITLE
                  Human response to shock and vibration


<TEST>
Description:         Phase 2 - Vehicle Data
Test Location:       outside track
Vehicle Type:        SUV
Seat Position:       Driver
Test Terrain:        gravel
Vehicle Speed:       15 mph

<SAMPLING>
Number of Channels:  3
Samples per channel: 25298
Sampling rate (Hz):  416.667
Signal duration (s): 60.7

<CHANNELS> -----------------------123456--12345678
01  seat x acceleration            m/s^2   XAC seat
02  seat y acceleration            m/s^2   YAC seat
03  seat z acceleration            m/s^2   ZAC seat

<DATA> ***************************************************
1(F7.2),2(F8.2) [Obsolete Fortran format … It is ignored]
   0.05    0.21    0.14
   0.05    0.19    0.13
   ----- etc...
```

Figure E-1. BCR data structure.

APPENDIX F. ABBREVIATIONS.

BCR	British Columbia Research
COV	Coefficient of Variation
DOD	Department of Defense
HDBK	Handbook
Hz	Hertz
ISO	International Standards Organization
km/hr	kilometers per hour
m/s^2	meters per second squared
mph	miles per hour
MTVV	Maximum Transient Vibration Value
NATO	North Atlantic Treaty Organization
OMS/MP	Operational Mode Summary/Mission Profile
PSD	Power Spectral Density
rad/s^2	radians per second squared
rms	root mean square
SAE	Society of Automotive Engineers
TARADCOM	Tank-Automotive Research and Development Command
TOP	Test Operations Procedure
VDV	Vibration Dose Value
WBV	Whole Body Vibration

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APPENDIX G. REFERENCES.

1. ISO 2631-1, Mechanical Vibration and Shock-Evaluation of Human Exposure to Whole-Body Vibration, Part 1: General Requirements, 1997.

2. ISO 2631-5, Mechanical Vibration and Shock-Evaluation of Human Exposure to Whole-Body Vibration, Part 5: Method for Evaluation of Vibration Containing Multiple Shocks, 2004.

3. SAE J1013, Measurement of Whole Body Vibration of the Seated Operator of Off-Highway Work Machines, August 1992.

4. DOD-HDBK-743A, Military Handbook Anthropometry of US Military Personnel, 13 February 1991.

For information only (related publications).

a. SAE 680091, Analytical Analysis of Human Vibration, February 1968.

b. SAE J1490, Measurement and Presentation of Truck Ride Vibrations, September 1999.

c. Wong, J.Y., Theory of Ground Vehicles, John Wiley & Sons, 1993.

d. Bekker, M.G., Introduction to Terrain Vehicle Systems, the University of Michigan Press, 1969.

e. Fix, G.A., "Tank-Automotive Research and Development Command (TARADCOM) Signal Analysis Program", September 1978.

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Forward comments, recommended changes, or any pertinent data which may be of use in improving this publication to the following address: Range Infrastructure Division (CSTE-TM), US Army Test and Evaluation Command, 2202 Aberdeen Boulevard, Aberdeen Proving Ground, MD 21005. Technical information may be obtained from the preparing activity: Commander, US Army Aberdeen Test Center (ATTN: TEDT-AT-AD), Aberdeen Proving Ground, MD 21005-5059 Additional copies can be requested through the following website: http://itops.dtc.army.mil/RequestForDocuments.aspx, or through the Defense Technical Information Center, 8725 John J. Kingman Rd., STE 0944, Fort Belvoir, VA 22060-6218. This document is identified by the accession number (AD No.) printed on the first page.